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Adapted Non-Circular Soft Turning of Bearing rings – Impact of process machine interactions on compensation potential

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Abstract

Distortion considerably influences manufacturing costs, especially if thin-walled parts are machined. To ensure a flexible economical machining, novel processes have to be developed to control distortion within the process chain. Then, reworking by straightening during quenching or by costly hard processing can be kept to a minimum. The fundamental concept of ‘Distortion Engineering’ is based on the inverse application of identified distortion potential to compensate geometric deviations.

In the case of thin-walled bearing rings the distortion is related to both, deviation of the wall thickness and the shape. These deviations originate mainly from an inhomogeneous material removal and uneven residual stress state in the workpieces subsurface caused by deformations due to clamping forces during the soft-turning. An adapted non-circular finishing cut can counteract the distortion. Previous work showed that the adaption of depth of cut depending on assessed geometric irregularities reduces deviations by at least two-third compared to non-compensated cutting. Compensation to zero deviation needs a deeper understanding; hence disturbances during the compensation cuts are investigated within this paper. An uneven change of subsurface residual stress state has a retro-active effect on the workpieces’ shape. Experimental results illustrate that the mechanical process loads are alternating with oscillation of the depth of cut. However, only an impact of adapted cutting on residual stresses perpendicular to the cutting direction (axial stresses) was detected. So far, it can be concluded that adapted cutting not leads to an unexpected change of out-of-roundness during subsequent heat treatment. Additionally, the results revealed that the compensation potential is highly affected by a change of workpieces’ deformation due to material removal during one longitudinal cut.

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1. Introduction

Parts of power trains, like gear wheels and bearing rings, are subject of increasingly strong requirements, with regard to load transmission, noise reduction and weight [1]. These requirements can only be met if a high accuracy of the workpieces’ geometry is retained.

Both, the weight-reduction of components and the rising demand on geometric tolerances result in ever increasing finishing costs at the end of production. Nowadays, a large amount of production costs is expended to reduce the distortion in the production process of steel parts. For example, already in 2000 Volkmuth et al. [2] estimated the costs arising from the

removing of distortion in manufacturing of parts of power trains up to 4% of the total sales. The authors illustrated the distortion related costs by translating the relative values into the worldwide manufacturing of bearing rings; the costs would amount up to 1 billion USD per year. Therefore, the control of distortion within the process chain of steel parts is crucial to ensure an economical manufacturing in the long term.

Every sub-process (i.e. casting, forming, hardening, cutting, etc.) induces distortion potential, which can cause undesired geometric deviations of the workpiece. The collaborative research centre (CRC) 570 ‘Distortion Engineering’ of the Deutsche Forschungsgemeinschaft analyses the mechanism of distortion along the

manufacturing chain. This research has identified several carriers of distortion potential (i.e. geometry, chemical composition, and residual stresses) as published by Zoch et al. in their review paper [3]. But only an uneven change of a carrier of distortion potential has a retro-active effect on geometric deviation [2, 3]. The fundamental concept of ‘Distortion Engineering’ is based on the inverse application of identified distortion potential to compensate geometric deviations.

In the specific case of bearing rings, the part distortion is related to the wall thickness (deviation of dimension) and out-of-roundness (deviation of shape). An investigation of Keßler et al. [4] within the CRC 570 revealed that the distortion generation mainly results from the applied clamping technique in turning, if the rings are quenched in a gas nozzle field. Then, the part distortion originates from elastic deformation of the workpiece during turning caused by clamping forces. The amount of this deformation depends on the clamping forces per jaw, the number of jaws and the workpieces’ stiffness [5]. The longitudinal circular cutting of a deformed surface leads to a varying material removal rate along the workpiece circumference (cf. Figure 1). Whereby, the clamping with three jaws results in an uneven triangular removal. Consequently, a triangular shape deviation of the machined surface occurs after releasing the ring. Additionally, as the material removal is always large at the vicinity of jaws and small between them, a harmonic wall thickness deviation is caused by internal and external cutting of the ring’s surfaces.

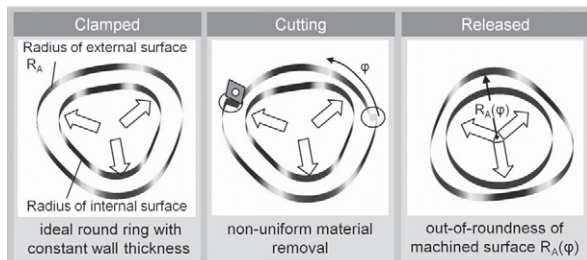


Fig. 1. Shape deviation due to inhomogeneous material removal caused by elastic deformation

Regarding shape deviations, workpiece clamping affects another mechanism apart from inhomogeneous material removal rate: the generation of a non-uniform residual stress state. During the turning of rings, clamping forces cause elastic bending stresses, which are stored in the workpieces surface by the plastic deformation caused by cutting [6] (cf. Figure 2). The generated uneven residual stresses in the workpieces subsurface inhibit a full springback after releasing the ring. Whereby, the amount of shape change is depending on the stored uneven bending moment which is,

according to Tönshoff [7], proportional to the thickness of the layer of residual stresses and its varying amounts. In conclusion, the residual stress state contributes to the shape deviation of thin-walled rings, which is observed after machining.

To reduce part distortion, several special clamping devices, like mandrels, are applied in the manufacturing of thin-walled rings. On the one hand mandrels ensure minimal part deformation, but on the other hand only one specific diameter can be clamped. Consequently, clamping devices would have to be changed for workpiece adaption. Now, if only a small number of rings with different clamping diameters have to be machined, high set-up times inhibit an economical machining of rings for low lot sizes. In conclusion, the choice of clamping devices is always a trade-off between achievable part quality and economical machining.

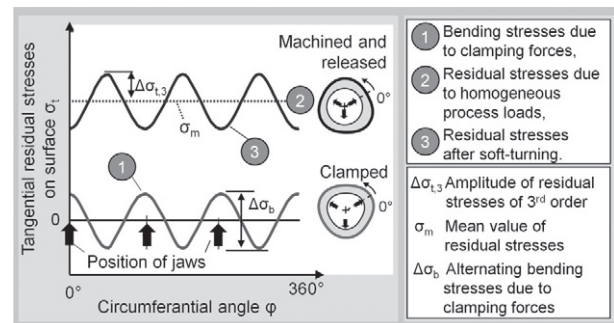


Fig. 2. Model of generation of uneven residual stresses in machined subsurface as published by Sölter [6]

2. Objective and procedure

2.1. General procedure and objective of compensation

To break up the trade-off between economic machining and the fulfillment of geometric tolerances the CRC has developed an adapted cutting method to reduce geometric deviation already in soft-machining (cf. Fig. 3). Therefore, deviations are measured within the turning center. Based on the evaluated data a non-circular tool track is calculated (cf. Fig. 3 B).

The method of geometric adapted cutting to reduce machining irregularities became public knowledge since it was first time discussed 1970 by Peklenik [8]. Also Shawky et al. [9] showed in 1998 that it was possible to minimize minor wall thickness deviation by an adapted cutting in the same manner as postulated in Fig. 3. The necessary superimposed dynamic fine positioning was realized using the axes of a conventional turning center. But even today, the ball screw drives do not offer the desired bandwidth at the long strokes, which is crucial for a real-time compensation of geometric deviations in soft-machining of thin-walled rings. Therefore, a tool

actuator driven by linear drives was developed and mounted in the working area of a conventional machine tool. The tool actuator (Fast Tool Servo) provides strokes up to $A = 300 \mu\text{m}$ at a maximum frequency of $f_{\text{max}} = 90 \text{ Hz}$. Further information regarding the control system and the mechanical design can be found in [10].

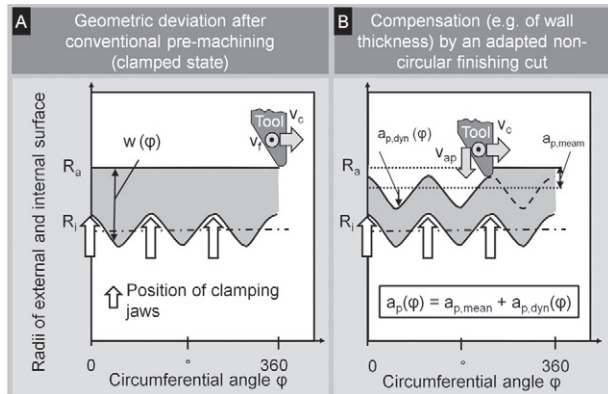


Fig. 3. A) Uneven wall thickness after conventional turning applying a three jaw chuck B) Minimization of deviations (here: wall thickness) by oscillating the depth of cut depending on the angular position.

In general, the objectives of compensation in soft-turning can be formulated as:

- Maintaining highest flexibility to ensure economic machining,
- Minimization of wall thickness (dimensional) deviation caused by inhomogeneous material removal,
- Minimization of out-of-roundness (deviation of shape) caused by inhomogeneous material removal and residual stresses, as well as
- Saving or even minimization of distortion potential.

Latter is crucial for the successful implementation of a compensation process within the manufacturing chain. In the worst case, geometric deviations can be reduced by adapted soft-machining, but at the same time it induces a large distortion potential in the workpiece (e.g. a high variation of residual stresses in high subsurface depths). Consequently, extraordinary large shape changes in subsequent processes like quenching would occur.

The strategy for the compensation of geometric deviations already in soft-machining comprises two steps. The shape irregularity is reduced with the final cut of the internal surface by adapted non-circular machining [11]. The final adapted cut of the external surface compensates the wall thickness deviation, based on the data of an ultrasound measuring system [12].

2.2. Measurement and evaluation of geometric deviation

A coordinate measuring machine (CMM) was used to measure the geometry of the machined parts with an uncertainty of approximately $1.5 \mu\text{m}$. The measurements comprise 256 measured points in circumferential direction at different workpieces heights. The measurement at the mid-height of the ring was used for assessing both, the geometric deviations before and after the compensation cuts. The CMM-data were evaluated according to the approach of Surm et al. [13], who split the circumferential deviations of a ring into their harmonic components based on the Fourier series representation. This approach enables to separate the shape deviations like ovality ($k = 2$) or triangularity ($k = 3$) from other deviations in order to correlate them with process parameters (cf. Fig 4).

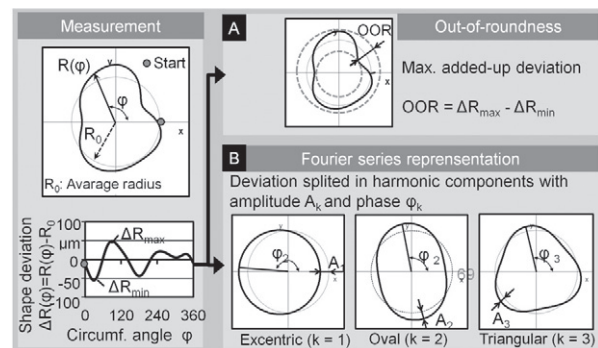


Fig. 4. Evaluation of the deviation from a specified geometry A) out-of-roundness B) harmonic coefficient of Fourier series.

2.3. Objective of investigation

The previously performed turning experiments revealed that the adapted cutting provides a reduction of the geometric deviations about at least two-third compared with non-compensated cutting (cf. Fig. 5). If segmented jaws are used instead of hardened gripper jaws, the out-of-roundness values can be reduced further. Nevertheless, a quite low overall wall thickness deviation of $20 \mu\text{m}$ and out-of-roundness of $51 \mu\text{m}$ remains [14].

Compensation to zero needs a deeper understanding of possible interactions. Finally, this knowledge has to be fitted into process models and implemented into the process controller. Initially, only values, which have an impact on workpiece deformation during finishing cut (cf. Fig. 3 B), are assumed to disturb the compensation process. Within this paper, entirely conceivable effects of selected parameters are discussed:

- Change of residual stress state and therefore distortion potential caused by oscillating the depth of cut and

- Change of elastic deformation due to material removal during one longitudinal cut.

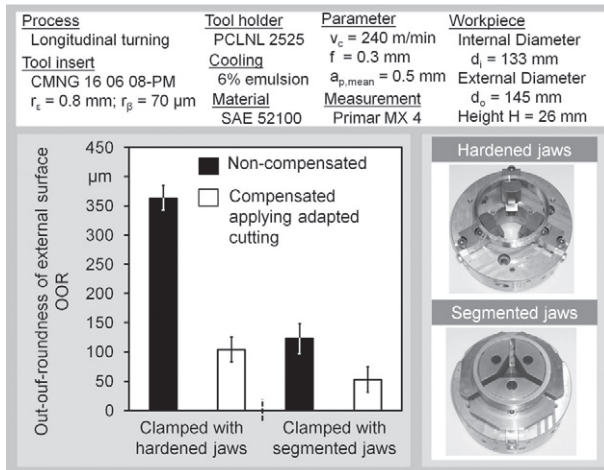


Fig. 5. Dependency of the compensation potential on applied clamping technique according to [14, 15].

2.4. Measurement and evaluation of process forces during adapted cutting and residual stresses

As introduced before, the generation or changing of residual stresses in workpieces' subsurface layers causes unfavorable changes of shape. The origins of residual stresses are thermo-mechanical loads caused by machining process [7]. It was suggested according to Kienzle [16] that oscillating the depth of cut $a_{p,dyn}$ leads to varying mechanical loads. By the way, the process forces actually alternate due to harmonic change of the cross-section of undeformed chip A_c (cf. Fig.6). The width of undeformed chip b is calculated according to [17]. As a large corner radius r_e related to the quite small average depth of cut $a_{p,mean}$ is applied, the cross-section of undeformed chip is comma-shaped. Therefore depth of cut has an impact on both, the width of the undeformed chip b and the effective undeformed chip thickness h_{eff} (cf. Fig. 6). Based on the calculation of the values of the undeformed chip, process forces can be predicted according to [16]. Both measured and predicted forces can be evaluated by calculation of Fourier series in order to compress the data.

The tool actuator provides no external sensors to measure cutting forces. In principle, forces during adapted cutting could be estimated by observing the value of current and acceleration [18]. Nevertheless, alternating cutting forces initially were measured analogously to the adapted cutting process. Therefore, a triangular shape deviation with different amplitudes was cut on the samples' surface. In the next step the workpiece was conventional circular machined. Consciously, the negative of the prior generated deviation was removed. The resulting cutting forces

were measured with a Kistler dynamometer. To avoid an impact of the clamping device solid cylinders instead of thin-walled rings were machined.

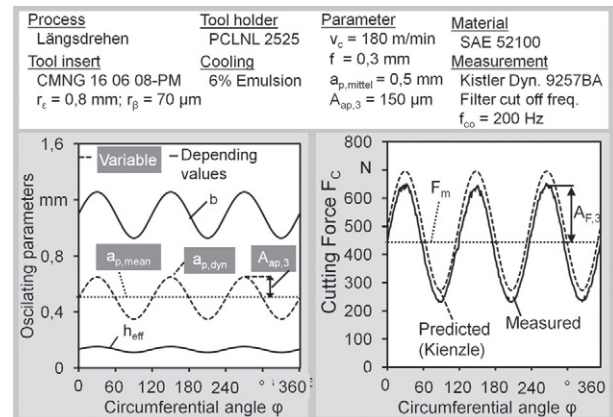


Fig. 6. Example of measured and predicted alternating cutting forces due to oscillating cutting parameters

Additionally to the indirect force measurement, some samples were only non-circular finished to investigate the impact of adapted cutting on the residual stresses. The surface was scanned every 20° in circumferential direction using a X-ray diffractometer .

3. Results

3.1. Alternating process forces caused by varying material removal

A material removal of 3rd order leads to alternating cutting forces (cf. Fig. 6). The 3rd order dominates also the resulting force variation. The relation between the amplitude of 3rd order of the depth of cut and the process forces is plotted in Fig. 7 A. The calculated standard deviation from measured data during cutting three samples is very low and therefore it can't be illustrated in Fig. 7 A. However, the variation of the force components increases with increasing amplitudes of the oscillating depth of cut $A_{ap,3}$. Whereby, the amplitudes of forces do not grow simultaneously. The change of the ratio between cutting force F_c and thrust force F_p indicates an appearance of a size effect in cutting in accordance with Lucca [19]. As introduced in chapter 2.4 thrust forces and cutting forces are predicted according to Kienzle. The difference between measured and predicted amplitudes $\Delta A_{F,3}$ are plotted in Fig. 7 B. Obviously, only the variation of cutting forces can be predicted precisely. Additionally, the measured mean values are listed in Table 1. Both, the standard deviation and mean values increase with decreasing amplitudes of oscillating depth of cut $A_{ap,3}$. Again, only average cutting forces can be predicted satisfactory with a maximum

deviation of 10%. The differences of mean values ΔF_m of measured and predicted thrust forces however, are considerably different (up to 35%).

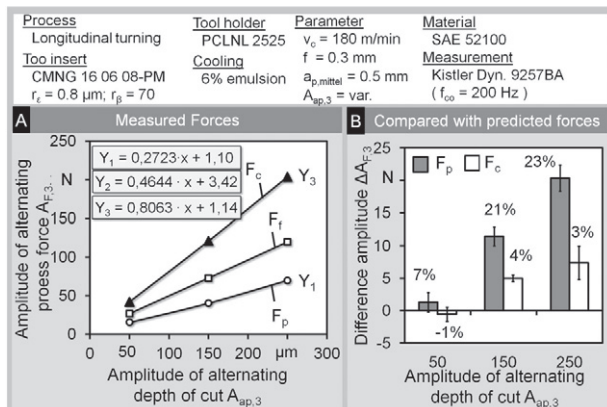


Fig. 7. Dependency of amplitude of depth of cut on amplitude of dynamic process forces

Table 1. Dependency of amplitudes of oscillating depth of cut on mean values of measured force data.

Variation	$A_{p,3}$ 50 μm	$A_{p,3}$ 150 μm	$A_{p,3}$ 250 μm
Force			
$F_{m,c}$ in N	469 ± 8	438 ± 2	446 ± 2
$F_{m,p}$ in N	287 ± 6	272 ± 3	275 ± 2

3.2. Impact of adapted cutting on residual stresses

Previously published investigations revealed no significant impact of adapted cutting on change of out-of-roundness observed after quenching [14]. But within the conducted compensation experiments only small amplitudes of oscillating depths of cut were applied. Therefore, it was concluded that adapted cutting induces a non-uniform residual stress state only at high variations of depth of cut $a_{p,dyn}$ [14]. First results of residual stress measurements indicate that oscillating the depth of cut has only a significant effect on axial residual stresses $\sigma_{ax}(\varphi)$ (cf. Fig. 8). If, in reverse conclusion, the adapted cutting has an impact on axial stresses, there should only be a relevant change of rings height during quenching.

In conclusion, from the results so far, the adapted cutting has no significant effect on change of out-of-roundness during quenching. Nevertheless, a change of out-of-roundness of thin-walled rings during quenching will occur, but it originates mainly from stored bending stresses caused by clamping according to Fig. 2. The adapted cutting itself induces a distortion potential parallel to workpieces' vertical axis. The resulting change of height is estimated in an amount of 1 per thousand of the ring height ($H_{ring} = 26 \text{ mm}$), because

only a thin layer of the cross section is affected by primarily mechanical loads of the turning process.

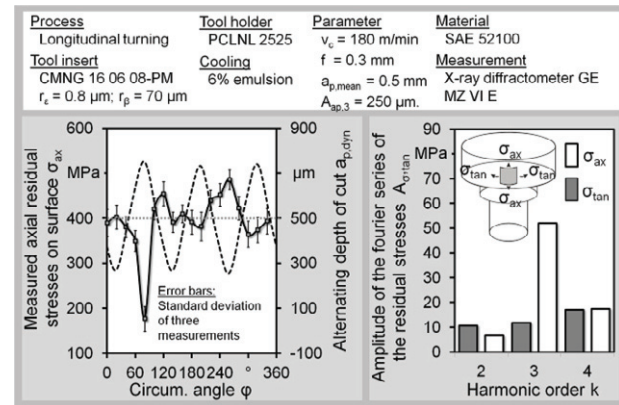


Fig. 8. Residual stress induced by varying material removal

3.3. Deviations caused by a change of deformation during one longitudinal compensation cut

If clamping forces are kept constant, the elastic deformation of a ring due to clamping forces increases with decreasing rings' stiffness. Hence, the clamping-ring-system reacts to progressing material removal with an increase of workpieces' deformation ΔA_3 during one longitudinal cut [15]. In general, the resulting deformation due to point loads can be predicted using analytical models as published e.g. by Malluck [5]. The calculated maximal changes of deformation ΔA_3 , which are achieved after a complete cut, depending on chosen mean depth of cut $a_{p,mean}$ are listed in Table 2.

Table 2. Predicted increase of triangular deformation due to clamping forces depending on material removal during one longitudinal cut.

a_p	Initial wall thickness w_0	Final wall thickness w_1	Decrease of moment of inertia ΔI_b	Increase of triangular deformation ΔA_3
0.25 mm	6.25 mm	6 mm	-61 mm ⁴	49 μm
0.5 mm	6.5 mm	6 mm	-127 mm ⁴	92 μm
1 mm	7 mm	6 mm	-275 mm ⁴	160 μm

In addition, the applied clamping technique has a major impact on workpieces' deformation during one longitudinal cut. Fig. 9 illustrates that the slope depends on clamping devices deformation characteristics. Low-deformation clamping technologies like a mandrel ensure a minimal change of rings' deformation during one longitudinal cut. Clamping with hardened jaws shows a strong increase of deformation. Furthermore, the experimental results shown in Fig. 9 indicate a set-off value. This constant value is obviously also affected by the chosen clamping technique. It is suggested that

this constant deviation is caused by cutting forces, which may also deform the ring, if the ring is clamped with a low number of jaws. As the calculation of the required tool-track to compensate geometric deviations (cf. Fig. 3) disregards a change of workpieces deformation during the compensational cut, the desired material removal overshoots. Therefore, the applied clamping technique has a major impact on the compensation potential by adapted cutting as shown in Fig. 4.

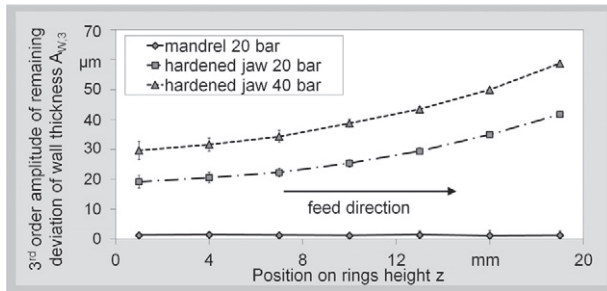


Fig. 9. Measured 3rd order amplitude of the remaining wall thickness deviation depending on the applied clamping technique and clamping force ($a_{p,mean} = 0.5$ mm).

4. Conclusion and outlook

The adapted cutting counteracts geometric deviations caused by applying flexible high-deformation clamping technique. Therefore, it is the key to economic machining of thin-walled rings with a large variety of versions. As a change of deformation due to progressing material removal during compensation cut is neglected, the compensation potential is limited to a certain value, always depending on applied clamping technique.

Although, oscillating the depth of cut leads to alternating mechanical loads in feed and cutting direction, a change of residual stress state only in axial direction could be assessed on workpieces' surface. To conclude the investigation, it has to be checked, if there is a dependency in workpieces subsurface. Additionally, as process forces also contribute to workpieces deformation during cutting [5, 15], the impact of alternating cutting forces will be analyzed in future work.

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